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THE TEVATRON GLOBAL RADIUS AND Øs SYSTEM*

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Abstract

It has been found to be practical to extract a turn-average measurement of bunch beam phase relative to cavity gap voltage. This Øs signal shows the bunch position on the R.F. wave throughout injection, acceleration and extraction, including coherent synchrotron oscillations when present.

In turn, the time derivative of Øs is a direct measure of global radial position error. We use the Øs signal, driving a phase shifter in the R.F. low-level system, to damp coherent synchrotron oscillations. Design and operation will be discussed including single beam bunch operation if available.

Introduction

Ever since the discovery of the principle of phase stability,[1,2] there has been interest in determining the phase position of bunches in an accelerator. Consider the phase angle Øs shown in Figure 1.

Point b represents the phase position of a bunch, center of charge, in an accelerating bucket; point c the phase position of a bunch in a stationary bucket, where Øs goes to zero. (Interestingly, this longitudinal stability principle was announced 8 years before strong focusing). An equilibrium phase angle can be calculated from the machine parameters including $\dot{B}$; in addition, operational interest attaches to dynamic measurements in the actual machine. Compared to a calculated equilibrium Øs, the measured value includes coherent synchrotron oscillation information of considerable diagnostic value. For simplicity, our variable Øs sums the stable phase angle and oscillations around it.

When it was decided to proceed with a programmed low-level RF system for the Tevatron[3], our interest in obtaining a a real-time Øs signal from the Tevatron increased considerably because without it the RF system is open loop; the machine has an undamped pole at the synchrotron frequency. This paper discribes what we did to obtain a radial damping signal as well as observe the motion of Øs over the machine cycle.

The Øs system finds the mean for all the bunches in the machine, averaged over several turns. Because of this averaging, the derived radius signal is termed a "global" signal and the effects of both betatron oscillations and local orbit distortions are highly supressed. (We have not detected them in the output).

The actual averaging is done by a quartz bandpass filter which has no measurable non-linearity; it sums the 1113th harmonic of all circulating bunches in the machine. The number of bunches can vary from 1 bunch to ~1000. After searching for commercially available filters, we selected one used in a single sideband transceiver. It is a four pole filter with a 2 KHz bandwidth and center frequency of 8.83 MHz. Seven were purchased so that phase and attenuation vs. frequency characteristics could be measured and compared. Three pairs were selected. Using 1.8 KHz bandwidth, the phase difference for the best pair was 1.0 degree and the worst pair 3.5 degrees. With the filters costing only $60 each, matching characteristics seemed worthwhile, and permitted higher accuracy in Øs. Besides, we later used one of the filters as a feedback element in an oscillator circuit. This became the 8.83 MHz local oscillator feeding mixer #1 (See Fig. 2).

The Tevatron is a proton synchrotron. Table I lists some parameters.

Table I

Machine Radius R_0	1000 Meters
Harmonic number h	1113
Injection Energy	150 GeV
Maximum Energy	1000 GeV
Average Momentum Compaction α	.0028
Peak Accelerating Voltage V Programmed+-----Typical Program:	Injection: 1 MV/Turn
	Acceleration: 1.7 MV/Turn
	Extraction: 1.2 MV/Turn
$\dot{E}$ (Typical)+	37.5 + GeV/Sec.

*These were the values for 6 RF stations. Recently, the number of RF stations has been increased to 8.[4]

Modus Operandi:

In this section we consider a machine that is accelerating beam acceptably. There is a reference closed orbit precisely defined by the frequency of the RF and the proton β. This orbit has a circumference equal to β x RF wavelength x harmonic number, or

$$2\pi R = \beta\lambda h = \frac{\beta c h}{F_{RF}} \qquad (1)$$

Note carefully that R is not identical to R_0, the machine radius. We may be steering the beam a few millimeters radially by intent. What is R? R defines the orbit the beam oscillates around and converges to as synchrotron oscillations are damped.

When undergoing synchrotron oscillations, the beam orbit is sometimes larger and sometimes smaller than the reference orbit, "breathing" in and out at the coherent synchrotron frequency in accord with the slight energy variation around synchronous energy. Plugging in values for the Tevatron, F_s for small amplitude oscillations is:

$$F_s = 87.6 \text{ Hz} \sqrt{V\cos\emptyset_s}\ \sqrt{\frac{150}{E}}$$

With V in megavolts and E in GeV. Thus F_s at injection is ~ 88 Hz and at 800 GeV extraction, ~ 42 Hz. Because the revolution frequency

$$F_{REV} = \frac{F_{RF}}{h} = 47.7 \text{ Kilohertz},$$

the number of turns per oscillation,

$$\frac{F_{REV}}{F_s} \text{ ranges from ~ 500 to 1200}$$

during the cycle.

Frequency and Radius

We see that the beam spends many turns circulating at a radius somewhat different from R, the

*Operated by Universities Research Association, Inc., under contract with the U.S. Department of Energy.

reference orbit, and accordingly generates a very slightly different frequency in a beam pickup. Call this frequency F_B. Differentiating eq. 1, we find the relation for a beam orbit offset by ΔR:

$$\frac{\Delta F}{F_{RF}} + \frac{\Delta R}{R} = \frac{\Delta\beta}{\beta} \qquad (1')$$

For our purpose Δβ/β is negligible in the range of 150 GeV and above, so to the 1st order in small quantities, we can write

$$\frac{\Delta F}{F_{RF}} \approx -\frac{\Delta R}{R}\text{, and for the Tevatron,}$$

$$\frac{\Delta F}{\Delta R} = -531 \text{ Hz/cm.}$$

Obtaining the Radial Signal

We know that the phase angle between two slightly different frequencies will progress at a rate proportional to the frequency difference ΔF:

Rate of phase change and frequency -

$$\frac{d\phi}{dt} = 2\pi\Delta F \qquad (2)$$

Therefore after we extract the angle Øs from the machine, we can measure its time rate of change which gives us ΔF, and by (1'), we have ΔR.

$$\Delta R \approx -\frac{R}{F_{RF}}\frac{1}{2\pi}\dot{\O}s \qquad (3)$$

F_{RF} varies ~2 parts in 10^5 over the cycle. We are willing to consider it constant for the purpose of (3). We have then, ΔR ≈ constant x $\dot{\O}$s; this displacement of the closed orbit as a whole from R is the global radius signal fed into the phase shifter to damp radial oscillations.

Because the above process of obtaining ΔF involves differentiation, it is necessary to achieve low noise. The phase detector is described in another paper,[8] this conference. Phase detector equivalent input noise is the most significant parameter determining the performance achievable in the Øs system.

At this point we will summarize a few things about Fig. 1. First, Øs varies and we want to see the variations. Second, the excursions of Øs, point b, are bounded to less than ±90°, and third, there is a slow variation in the period of the wave acd - the period decreasing by about 2 parts in 10^5 as beam accelerates.

Now refer to Figure 2.

We identify a signal F_{RF} from the accelerating cavity and another signal F_B from beam pickup [5 6 7] in the ring. F_{RF} is a sine wave but F_B is a beam bunch signal with missing bunches and harmonics at all multiples of the circulation frequency up to more than 2 GHz. It is harmonic #1113 that we want; the bandpass filter isolates it. Because the center of the filter was 8.83 MHz (not 53) we heterodyned both F_{RF} and F_B to 8.83.

Heterodyning to Eliminate Frequency Shift Due To Acceleration

The technique to eliminate frequency shift due to acceleration takes three mixers but has the notable advantage that the 1024 Hz change in F_{RF} due to β change is identically removed. The result is stable 8.83 MHz signals for both bandpass filters - only the Øs variation remains. The scheme goes as follows: there is a local oscillator at 8.83 MHz (constructed from the third filter). This frequency is mixed with cavity RF in mixer #1 to produce at the output of the 37 db ENI an upper sideband of F_{RF}. Mixers # 2 & 3, using the 61.9 MHz, remove the 1024 Hz frequency change and also translate both signals from 53.1 MHz down to 8.83. Thus there is a signal 61.9 MHz - F_{RF} entering filter 1 and a signal 61.9 MHz - F_B entering filter 2. All mixing is phase transparent; the phase detector working at 8.83 MHz sees the same phase angle as exists between F_{RF} and F_B. This angle is the Øs desired.

Because the bandwidth of the filters is 2 KHz, considerably narrower than the spacing between the revolution frequency harmonics which occur every 47.7 KHz, 8.83 MHz "F_B" is a continuous sine wave regardless of missing bunches in the original beam signal. The filter idea was selected as the method of filling in for missing beam bunches, and has worked well in practice. There is an external circuit called the "Beam Regenerator", which takes the 8.83 MHz, "F_B" continuous wave and mixes it again with the 61.9 MHz to reproduce a continuous 53.1 MHz sine wave. This wave stays precisely in phase with the bunches.

Performance

We can see Ø s to within about a degree in long term stability and about .01 degree dynamically. This corresponds to seeing PM sidebands at -85 dbc and radial oscillations below 10 microns with machine intensity of ~ 1 E 13 protons.

Beam damping is illustrated in Fig. 3. The upper trace is beam intensity (~ 7 E 12 PROTONS) the lower trace is Øs, with injection into the Tevatron at the start of the trace. Note the approximate damping response time of 100 MSEC at injection. Fig. 4 illustrates the same conditions without any damping until about 1.5 seconds after injection. Fig. 5 is with damping and shows beam intensity and Øs in the Tevatron from time of injection through end of extraction. We expect damping to occur as e^{-kn}, where n is the number of turns and

$$k = \frac{\hat{g}\,\alpha R}{2\beta^2 E}\text{. The value of } g$$

for the Figures was 30 KeV/mm and E was 150 GeV so we expect e-fold damping in 3500 turns or 73 millisec.

Remarks

The error gain is programmed over the accelerator cycle according to an experimental curve.

The dotted lines in Fig. 2 represent automatic level control that has been discussed but not implemented yet. Without the automatic level control, there is a 40 db dynamic intensity range. The detailed reasons for the anti damping of the open-loop have not been explored. The damping factor could be increased about 5 times with foreseeable improvements.

Acknowledgements

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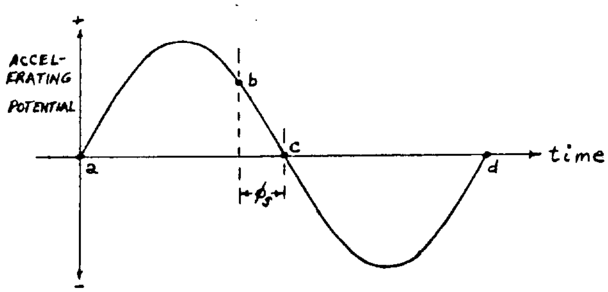

Figure 1. Illustrating Phase Stability

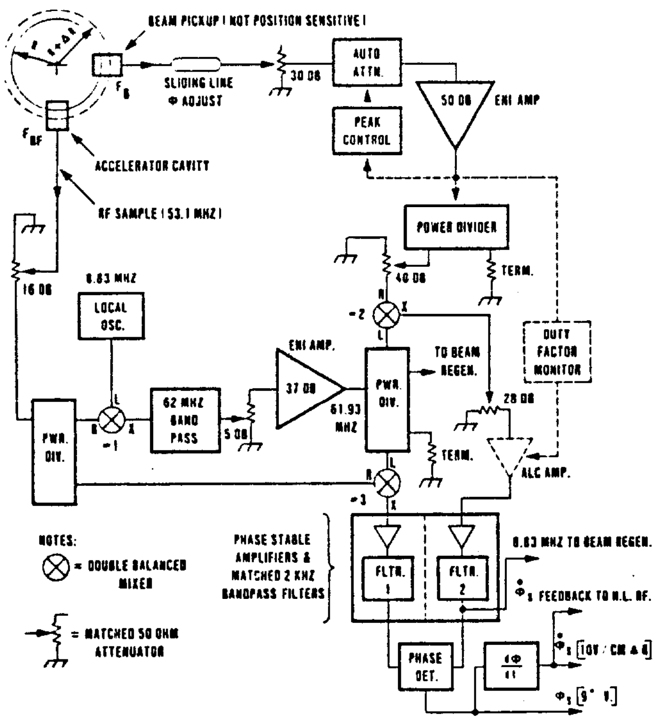

Figure 2.

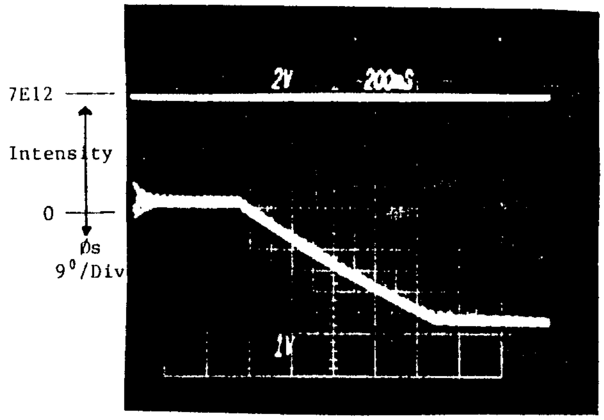

Figure 3. 200 Millisec/Div.

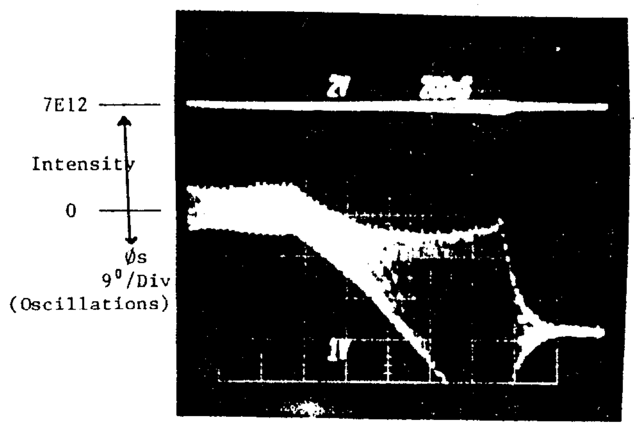

Figure 4. 200 Millisec./Div.

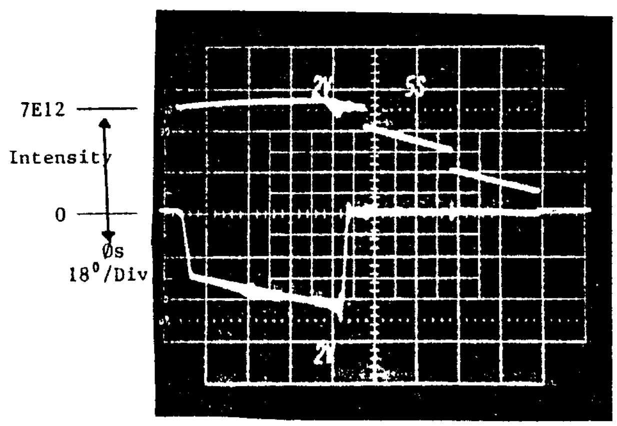

Figure 5. 5 Sec./Div.